# Hyperpycnal sediment discharge from semiarid southern California rivers: Implications for coastal sediment budgets

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## ABSTRACT

**Southern California rivers discharge hyperpycnal (river density greater than ocean density) concentrations of suspended sediment (>40 g/L, according to buoyancy theory) during flood events, mostly during El Niño–Southern Oscillation (ENSO) conditions. Because hyperpycnal river discharge commonly occurs during brief periods (hours to occasionally days), mean daily flow statistics often do not reveal the magnitude of these events. Hyperpycnal events are particularly important in rivers draining the Transverse Range and account for 75% of the cumulative sediment load discharged by the Santa Clara River over the past 50 yr. These events are highly pulsed, totaling only ~30 days (~0.15% of the total 50 yr period). Observations of the fate of sediment discharge, although rare, are consistent with hyperpycnal river dynamics and the high likelihood of turbidity currents during these events. We suggest that much of the sediment load initially bypasses the littoral circulation cells and is directly deposited on the adjacent continental shelf, thus potentially representing a loss of immediate beach sand supply. During particularly exceptional events (>100 yr recurrence intervals), flood underflows may extend past the shelf and escape to offshore basins.**

**Keywords:** hyperpycnal, suspended sediment, river plume, southern California, Transverse Range.

## INTRODUCTION

River water introduces a positive-buoyancy (hypopycnal) flux to the coastal ocean, but if river discharge is heavily laden with suspended sediment, discharge density will increase, which enhances the potential for hyperpycnal (river density greater than ocean density) plumes. Hyperpycnal river discharge introduces dense, sediment-laden currents directly to the seabed, which greatly enhances the potential for turbidity currents offshore (Normark and Piper, 1991). Negatively buoyant river discharge is not necessarily required to initiate dense gravity flows of sediment, such as have been observed off the mouth of the positively buoyant Amazon and Eel Rivers (Kineke and Sternberg, 1995; Cacchione et al., 1999), and is suggested by laboratory work by Parsons et al. (2001). However, hyperpycnal discharge will produce turbidity currents with greater frequency than positively buoyant river discharge (Mulder and Syvitski, 1995).

The limited investigations of the dynamics of hyperpycnal river plumes suggest that the freshwater in the plume will eventually exhibit positive buoyancy as suspended sediment settles from the turbidity current (Chao, 1998). This partitioning of water and sediment, combined with internal waves along the upper plume boundary, is responsible for unusually rapid dissipation of the Yellow River hyperpycnal plumes. Because of these dynamics, Wright et al. (1988) suggested that initial fine-sediment dispersal from hyperpycnal rivers may be much more confined than that from hypopycnal flow, which can expel sediment great distances within extensive surface plumes. If a hyperpycnal river plume encounters a steep slope (such as a submarine canyon), however, sediment transport by gravity currents may extend to deep ocean basins (Mulder et al., 2001).

Small and medium rivers that drain mountainous terrain are responsible for most of the known hyperpycnal rivers (Mulder and Syvitski, 1995), largely because of their high sediment-production rates (Milliman and Syvitski, 1992). Most of these hyperpycnal rivers are located in eastern Asia, while hyperpycnal discharges from North American rivers are thought to be rare (recurrence interval of the order of ~100 yr), happening only during ''exceptional'' or ''maximum possible'' flooding events (Mulder and Syvitski, 1995). Here we show that the discharge of the southern California rivers, which were not included in Mulder and Syvitski's (1995) analyses, is often hyperpycnal during El Niño–Southern Oscillation (ENSO) related floods.

## SOUTHERN CALIFORNIA RIVERS

The rivers of semiarid southern California (Fig. 1) drain a tectonically active landscape and are thought to be responsible for most (80%–95%) of the sand contributions to the local littoral cells (e.g., Brownlie and Taylor, 1981). Sediment discharge from these rivers, however, is infrequent, occurring during and immediately following large winter precipitation events. Annual variability of sediment discharge reflects the highly variable winter rainfall, which is forced in turn by regional and global climatic patterns, particularly ENSO (Mo and Higgins, 1998; Inman and Jenkins, 1999). On average in the southern California rivers, 50% of the suspended-sediment discharge occurs during just ~0.1% of the time (~1 day every 3 yr; Warrick, 2002). As a result, ~90% of the historic river-sediment loads have occurred during ENSO years, although not all ENSO years are marked by

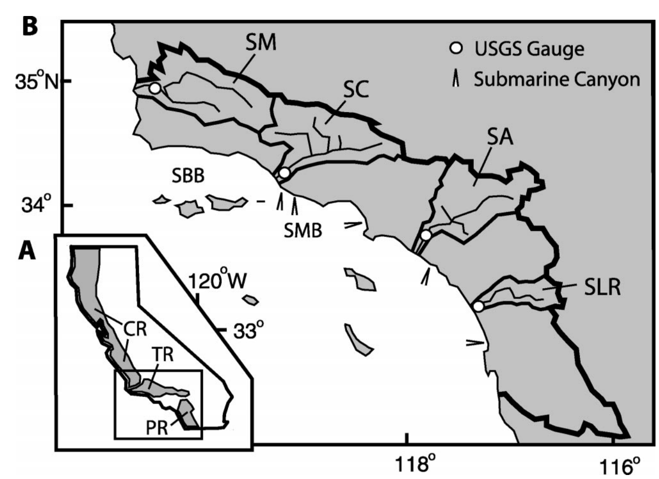


**Figure 1. California coastal mountain ranges and southern California watershed. A: Major mountain ranges of coastal California (CR—Coast Range; TR—Transverse Range; PR—Peninsular Ranges). Box shows extent of map in B. B: Southern California watershed. Rivers and U.S. Geological Survey (USGS) gauges included in this work are identified (SM—Santa Maria River, USGS 11141000; SC—Santa Clara River, USGS 11113920 and 11114000; SA—Santa Ana River, USGS 11078000; SLR—San Luis Rey River, USGS 11042000). Two offshore basins noted in text are also labeled (SBB—Santa Barbara Basin; SMB—Santa Monica Basin).**

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high precipitation or high sediment discharge (Inman and Jenkins, 1999).

Rates of sediment production from the southern California rivers depend upon bedrock geology, rates of tectonic uplift, land use, and precipitation (Brownlie and Taylor, 1981; Warrick, 2002; Willis and Griggs, 2003). Inman and Jenkins (1999) showed that the rivers of the Transverse Range have sediment yields approximate two-fold greater than those of the Coastal Range and approximately an order of magnitude greater than the Peninsular Ranges (see Fig. 1 for locations). As a result, the Santa Clara River, which drains the Transverse Range (Fig. 1), is the dominant sediment source of the southern California margin (Schwalbach and Gorsline, 1985).

## HYPERPYCNAL DISCHARGE FROM SOUTHERN CALIFORNIA RIVERS

Simple buoyancy theory suggests a hyperpycnal threshold of 40 g/L for southern California rivers (average ocean density is ~1025 kg/m$^3$; Warrick, 2002), although hyperpycnal conditions may be induced through convective instabilities from a surface hypopycnal plume with sediment concentrations as low as 1 g/L (Parsons et al., 2001). Here we use 40 g/L as a conservative hyperpycnal threshold to analyze data from the large 1969 floods, during which discharge and suspended sediment were collected at 1–4 h intervals (Waananen, 1969), and then discuss these data in relation to long-term sediment-discharge budgets. We focus on four rivers that represent the diverse settings of southern California (Fig. 1): the combined Coastal and Transverse Ranges (Santa Maria River), the Transverse Range (Santa Clara River), the heavily urbanized basins (Santa Ana River), and the Peninsular Range (San Luis Rey River).

### Floods of 1969

Large storms during late January and late February 1969 produced widespread flooding events and record river discharges throughout southern California. Suspended-sediment concentrations during these events exceeded the 40 g/L hyperpycnal threshold for periods of hours to days (February data shown in Fig. 2). Peak instantaneous suspended-sediment concentrations in both the Santa Clara and Santa Ana Rivers were 150 g/L, which would have produced a negative-buoyancy anomaly ~3-fold the absolute value of fresh water entering the sea (−0.66 vs. 0.24 m/s$^2$; calculations are available[1]). Hyperpycnal conditions were more frequent and sustained in the Santa Maria, Santa Clara, and Santa Ana Rivers than in the San Luis Rey River.

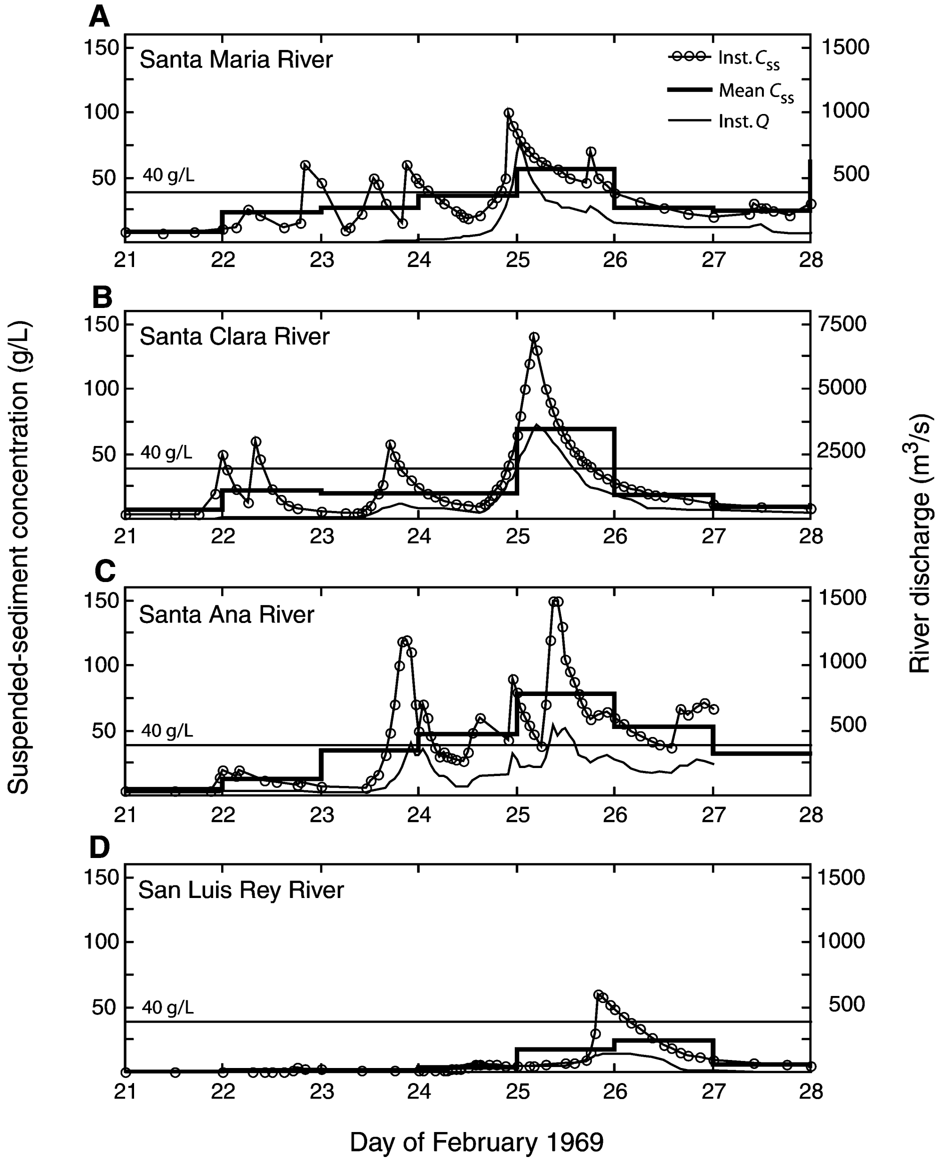


**Figure 2. A–D: Suspended-sediment concentration and river discharge for four southern California rivers during peak flooding of February 1969 (after Waananen, 1969). Plotted data: instantaneous sediment concentrations (Inst. $C_{ss}$) reported at 1–4 h intervals (symbols at each sample), average daily sediment concentrations (Mean $C_{ss}$) calculated from ratio of daily sediment load to daily water discharge, and river-flow rate reported at 1–4 h intervals (Inst. $Q$). Theoretical hyperpycnal threshold of 40 g/L is shown with a gray horizontal line.**

The suspended-sediment concentrations (Fig. 2) were also highly dynamic, often fluctuating over an order of magnitude each day; as such, the mean daily suspended-sediment concentrations often belie shorter-term variations. In the San Luis Rey River, for example, daily sediment concentrations on 25 and 26 January were 17 and 24 g/L, respectively, whereas instantaneous concentration exceeded 50 g/L for 4–5 h (Fig. 2D), during which ~40% of the flood-derived load was discharged. Peak instantaneous sediment concentrations in all four rivers were commonly about twice the mean daily concentrations (Fig. 2).

### Hyperpycnal Frequency

To assess the relative frequency of hyperpycnal river discharge, we compiled instantaneous river-sediment sampling and peak-discharge data for the four representative rivers. In these analyses, discharge has been normalized by the mean annual flood discharge ($Q_{maf}$, statistically defined to be the 2.33 yr recurrence interval peak discharge) for each river.

For the two rivers draining parts of the Transverse Ranges (Figs. 3A, 3B), the 40 g/L hyperpycnal threshold is surpassed during flows of <1 to 3 × $Q_{maf}$ (analogous to ~1 to 4 yr recurrence intervals). This finding suggests that these rivers frequently produce hyperpycnal events. Sediment concentrations in

[1]GSA Data Repository item 2003113, calculations of buoyancy and particle sizes in a hyperpycnal plume turbidity current, is available online at www.geosociety.org/pubs/ft2003.htm, or on request from editing@geosociety.org, or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

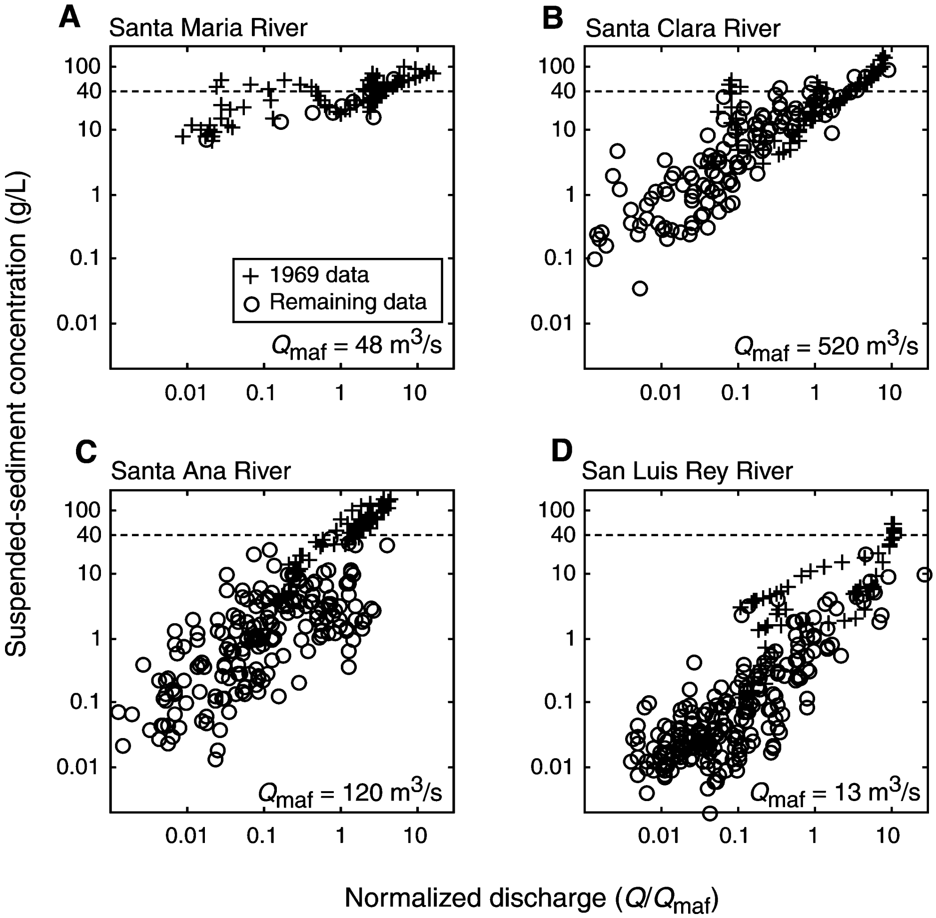


**Figure 3. A–D: Suspended-sediment sampling results for four southern California rivers from two 1969 events (pluses; Waananen, 1969) and remaining U.S. Geological Survey (2001) data record (circles). River-flow rate has been normalized by mean annual floods ($Q_{maf}$) for each river for ease of comparison. Hyperpycnal threshold of 40 g/L is shown with dashed line.**

the Santa Ana River (Fig. 3C) surpassed the hyperpycnal threshold at $\sim 1 \times Q_{maf}$ during the 1969 events (pluses), but data from the other years (circles) indicate that this relationship is exceptionally variable. This is consistent with the observation of Willis and Griggs (2003) that the Santa Ana River has exhibited decreasing trends in sediment output over the past three decades due to dam regulation. The San Luis Rey River (Fig. 3D) shows evidence of surpassing the buoyancy threshold only during much larger events ($\sim 10 \times Q_{maf}$) that are therefore much less frequent ($\geq$10 yr recurrence intervals). All the southern California rivers regularly exceed the lower 1 g/L threshold of Parsons et al. (2001).

**Total Hyperpycnal Loads**

The U.S. Geological Survey has computed daily loads and mean sediment concentrations for the 1960s to 1980s, which can be extended by using power-law rating curves of daily water flux vs. daily sediment load (e.g., Brownlie and Taylor, 1981). For all rivers except the Santa Ana (which has highly variable sediment discharge relationships), the $r^2$ values of these sediment-load rating curves are 0.9 or higher. It is important to note that these mean daily sediment loads and concentrations are conservative estimates of the actual hyperpycnal fluxes because of the rapid dynamics of sediment concentrations in southern California rivers (Fig. 2). Thus, to assess the proportion of the daily sediment loads discharged under hyperpycnal conditions, we assumed that the percentage of hyperpycnal discharge increased linearly from 0% at 20 g/L (average daily concentration) to 100% at 40 g/L, which is consistent with the data in Figure 2.

Thus, we compiled and computed daily loads for water years 1950–1999 for all rivers but the Santa Ana (which has highly variable sediment discharge) and the Santa Maria (where the stream gauge was discontinued after 1989; for this river we used 1940–1987 data). Although the $\sim$50 yr cumulative loads for the four rivers varied by nearly 50-fold ($3.7 \times 10^6$ t for the San Luis Rey, $170 \times 10^6$ t for the Santa Clara), hyperpycnal loads accounted for $\sim$40% (San Luis Rey) to $\sim$75% (Santa Clara).

Years with large annual sediment loads tend to have the highest rates of hyperpycnal discharge (Fig. 4). For the Santa Maria and Santa Clara Rivers, annual sediment loads of $>1 \times 10^6$ t, tend to be dominated by hyperpycnal discharge, whereas lower annual loads are

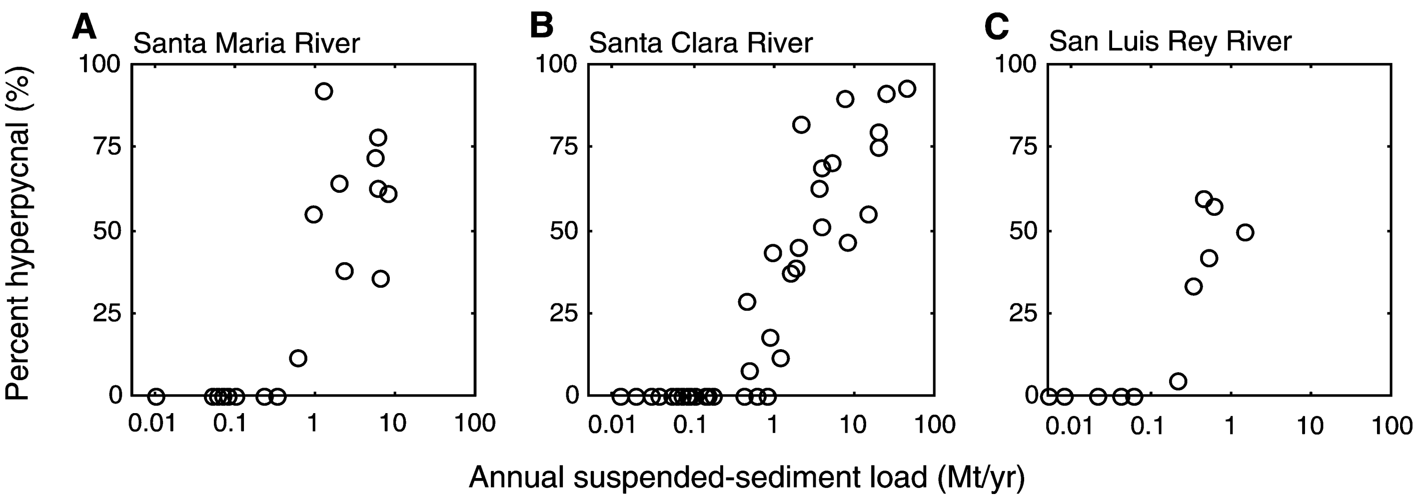


**Figure 4. A–C: Percentage of annual sediment load discharged during hyperpycnal river conditions (>40 g/L) for four southern California rivers (see text for computation methods).**

mostly hypopycnal. The threshold for the San Luis Rey River is $\sim 0.5 \times 10^6$ t, which was reached only 5 times in the past 50 yr (1969, 1980, 1983, 1995, 1998). If the convective-instability threshold of 1 g/L (Parsons et al., 2001) is used, >95% of the suspended-sediment discharge from the southern California rivers can be considered hyperpycnal.

## IMPLICATIONS FOR SEDIMENT DISPERSAL

The general lack of field data, unfortunately, limits our ability to define the fate of sediment discharged from southern California rivers. A census of suspended matter in the surface waters off the California coast during a large 1998 ENSO flood suggests that only a small percentage of the flood-derived sediment was in the surficial waters; presumably most of the sediment was subsurface, which agrees with hyperpycnal dispersal (Mertes and Warrick, 2001). Oceanographic observations off the Santa Clara River during two large storms confirmed this observation and suggest that sediment was primarily dispersed from the river along the seabed (Warrick, 2002).

Drake (1972) described flood deposits offshore of the Santa Clara River immediately following the 1969 floods. Between 75% and 95% of the total sediment load could be accounted for on the continental shelf within a distance of 20 km from the mouth. Flood-deposit thickness was greatest near the river mouth (to 15 cm thick) and thinned to negligible thicknesses on the slope. It is interesting to note that Drake's (1972) observations suggest that significant amounts of flood-derived sand were transported beyond the littoral zone during the 1969 floods. Flood sand was deposited in a river-mouth delta (consisting of gravel and sand, presumably from river bedload) and was transported offshore to a distance 1–1.5 km seaward of the beach, where sandy flood facies (~50% sand) occurred to depths of ~20 m.

Turbidity currents related to river floods also have extended past the continental shelf (>100 m isobath) and into surrounding basins during extremely wet winters. For example, three of the six major turbidites <500 yr old in the Santa Monica Basin (Fig. 1) are associated with years of exceptional river discharge (ca. 1600, 1885, 1969; Gorsline, 1996). The laminated sediments of the Santa Barbara Basin (Fig. 1) reveal one such turbidite dated to A.D. 1605 ± 5 yr (Schimmelmann et al., 1998), which is coincidental with the Santa Monica Basin flood turbidite.

These few available observations and data imply that flood-derived sediment is transported along the seabed and is deposited mostly on the shelf adjacent to or offshore from the river mouth, presumably by hyperpycnal currents. This hypothesis is supported by calculations using Reynolds (1987) turbidity-current equations (calculations are available; see footnote 1), which suggest that medium to coarse sand would be transported by Santa Clara River hyperpycnal currents on the inner shelf (southern California river suspended sediment is, on average, 25% sand [>62 μm] and 75% fines; Willis and Griggs, 2003). Thus, hyperpycnal river plumes may be responsible for transporting river sand offshore of the beach, resulting in a long-term loss of this potential beach sand source.

Future work is needed to describe the hyperpycnal character and dispersal processes of southern California rivers. If significant amounts of sand are being transported offshore of the littoral cells, it is important to evaluate the spatial and temporal scales of that material returning to the beach (if at all). Results from this reevaluation may necessitate modification of beach sand budgets (e.g., Willis and Griggs, 2003). Further, the rivers of southern California are the largest sources of pollution to the Southern California Bight (Bay et al., 1999). Pathways of many of these pollutants are associated with fine-sediment transport, which will be significantly different under hyperpycnal vs. hypopycnal dispersal conditions. To describe particulate and pollutant dispersal in this region adequately, extensive river- and ocean-monitoring efforts (especially during peak-discharge conditions) should be employed.


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